Chapter 7

Results And Discussions

7.1 Application of AFP Method for unaligned permeance calculation

In this chapter, results in modified unaligned permeance calculation for single tooth (6/4) and multi tooth (12/10 and 24/22) per pole SRMs is presented. This is followed by error analysis of results between computed data and Conformal Tranformation Method data. The error analysis between computed data and Mile's Method data [4] is also presented in this section. The discussions of results in term of their accuracies between developed model and compared methods are also presented in this section.

The modified model developed was evaluated to provide the values of unaligned permeance for various configurations (6/4, 12/10 and 24/22). Program simulations have also been carried out to determine the optimum values of the unaligned permeance for single tooth and multi tooth per pole SRMs.

7.2 Motor dimensions

The motor dimensions include single tooth (6/4) and multi tooth (12/10 and 24/22) per pole SRMs. All the dimensions are shown in the following section.

7.2.1 Input motor dimensions for single tooth (6/4) per pole SRM

The motor dimensions for single tooth (6/4) are given as:

Number of stator tooth	6
Number of rotor tooth	4
Split ratio	0.563295
Back of core width	13.4697 mm
Stator outer diameter	165.1 mm
Rotor outer diameter	93.1 mm
Stator tooth width	25.3882 mm
Rotor tooth width	25.4136 mm
Rotor slot depth	11.8872 mm
Air gap	0.298 mm

7.2.2 Input motor dimensions for multi tooth (12/10) per pole SRM

The motor dimensions for multi tooth (12/10) are given as:

Air gap	0.254 mm
Pole neck height	6.7 mm
Back of core width	12.46 mm
Stator outer diameter	165.1 mm
Rotor outer diameter	92.5 mm
Stator tooth width	12 mm
Rotor tooth width	12 mm
Rotor slot depth	12.5 mm

7.2.3 Input motor dimensions for multi tooth (24/22) per pole SRM

The motor dimensions for multi tooth (24/22) are given as:

Pole neck height	6.7 mm
Pole neck width	23.5 mm
Tooth height	5.0 mm
Back of core width	15 mm
Stator outer diameter	162.5 mm
Rotor outer diameter	92.5 mm
Stator tooth width	4.6 mm
Rotor tooth width	4.6 mm
Air gap	0.254 mm
Taper tooth angle	2°
Number of stator pole	6
Rotor slot depth	12.5 mm

7.3 Discussion of results

This section presents the error analysis and discussions of results for the developed model, Conformal Transformation Method [44] and Mile's Method [4]. The simulation software for this modified unaligned permeance is shown in Appendix 7.3 (Fig 7.3A, Fig 7.3B and Fig 7.3C).

Motor Types	Computed data	Conformal Transformation	% error
Single tooth (6/4)	4.501	4.202	7
Multi tooth (12/10)	5.375	5.576	4
Multi tooth (24/22)	4.317	4.442	3

Table 7.1: Error analysis showing the comparison between computed unaligned permeance using AFP and that obtained by Conformal Transformation Method.

Motor types	Computed data	Mile's method	% error
Single tooth (6/4)	4.501	4.557	1
Multi tooth (12/10)	5.375	5.552	3
Multi tooth (24/22)	4.317	6.180	23

Table 7.2: Error analysis showing the comparison between computed unaligned permeance using AFP and that obtained by Mile's Method.

The unaligned permeance data for Conformal Transformation Method (Appendix 7.3a) are obtained from a computer program based on the Schwarz-Christoffel transformation equation [44]. The unaligned permeance data for Mile's Method are obtained based on the calculation performed by Mile [4].

From Table 7.1, the difference between computed method and Conformal Transformation Method for single tooth per pole SRM (6/4) is 7%. The percentage error for multi tooth per pole SRMs (12/10 and 24/22) are 4% and 3% respectively. The high percentage error for single tooth per pole SRM (6/4) is expected. This is due to the fact that Conformal Transformation Method is only suitable for multi tooth per pole SRMs (12/10 and 24/22) not single tooth per pole SRM (6/4).

Table 7.2 presents the absolute percentage error for multi tooth per pole SRM (24/22) obtained by computed method and Mile's Method. From this table, it can be seen that the modified technique for unaligned permeance calculation produced a better approximation of unaligned permeance leading to more accurate performance of SRMs.

From table 7.2, the percentage errors for single tooth per pole 6/4 SRM and multi tooth per pole 12/10 and 24/22 SRMs are 1%, 3% and 23%, respectively compared to computed method. Comparing Tables 7.1 and 7.2 it can be seen that the computed value for 24/22 SRM is more accurate compared to Mile's Method. Since the Conformal Tranformation Method is known to be accurate in representing the multi tooth per pole SRMs, therefore the method propose in this thesis is acceptably accurate in determining the unaligned permeance of multi tooth per pole SRMs.

Thus, generally the proposed AFP technique for calculating unaligned permeance can provide a good approximation of unaligned permeance for single tooth and multi tooth per pole SRMs. This algorithm for unaligned permeance developed in this thesis is suitable for designing and predicting the performance of SRMs. More accurate results can be obtained if the program is optimised by refining the flux contours to be different from the one proposed in this thesis.

7.4 Static analysis results

In this section, static analysis results arising from the developed model and experimental data is presented. From the error analysis the values of modified unaligned permeance can be used for the static analysis in this thesis. The proposed simplified block modeling technique for static analysis has been adopted in evaluating the aligned and unaligned flux linkages against current.

7.5 The motor dimensions in application of static analysis

The motor dimensions (for single tooth (6/4) per pole SRM), obtained from the University of Newcastle, U.K [45] are used in determining the program simulation results. These dimensions are shown below:

Stator outer diameter	0.1651 m
Stator core length	0.1080 m
Stator tooth width	0.0253882 m
Back of core width	0.0134697 m
Bore diameter	0.093 m
Rotor core length	0.1143 m
Rotor tooth width	0.0254136 m
Rotor slot depth	0.0118872 m
Air gap width	0.000298 m
Turn per phase	1150

7.6 Comparison the flux linkage with experimental data

This section presents the error analysis and discussions between computed data and experimental data. The experimental data (for single tooth (6/4) per pole SRM) are obtained from the University of Newcastle, U.K [45].

Current (Amp)	Aligned flux linkage	Experimental data	% error
1.0	4.861	4.756	2
2.0	5.395	5.200	4
3.0	5.691	5.511	3
4.0	5.896	5.689	4
5.0	6.058	5.867	3
6.0	6.191	6.000	3
7.0	6.305	6.178	2
8.0	6.399	6.267	2
9.0	6.483	6.356	2
10.0	6.560	6.444	2

Table 7.3: Error analysis showing the comparison between computed aligned flux linkage and experimental data

Current (Amp)	Unaligned flux linkage	Experimental data	% error
1.0	0.435	0.444	2
2.0	0.870	0.800	9
3.0	1.305	1.244	5
4.0	1.740	1.600	9
5.0	2.174	2.000	9
6.0	2.608	2.400	9
7.0	3.041	2.844	7
8.0	3.470	3.289	6
9.0	3.895	3.644	7
10.0	4.302	4.000	8

Table 7.4: Error analysis showing the comparison between computed unaligned flux linkage and that obtained by experimental data.

From Table 7.3, it can be seen that the absolute percentage errors for all cases are less than 5%. Table 7.4 presents the absolute percentage error for unaligned flux linkage and experimental data. This table shows that the maximum percentage error is 9% and the minimum percentage error is 2%. Thus, from both table it is obvious that the Simplified Block Model used in this thesis is suitable for predicting the performance of single tooth per pole SRM. The results from the simulation for static analysis are shown in appendix 7.6 (Fig 7.6A and Fig 7.6B).

The output of multi tooth (24/22) per pole SRM is shown in Appendix 7.6a (Fig 7.6aA and Fig 7.6aB).

7.7 The CAD program

The proposed CAD program was running on PC 486-16 MHz. For a given set of specifications, there may be more than one set of motor dimensions to be evaluated in this CAD (see Appendix 7.7). Tests have also been carried out to determine the optimum values of motor parameters i.e motor dimensions, voltage, efficiency, torque average, power developed, volume and etc. The input specifications consist of power, current loading, speed and stator outer diameter.

The input specifications for CAD program are given as:

Power developed	100 watts
Current loading (Asp)	25000
Speed	100 rpm
Stator outer diameter	0.1651 m

The output from the CAD program simulation as shown in the next Section.

7.8 Results of CAD program simulation

The motor parameters from the CAD program simulation for single tooth per pole SRM are shown below.The results from developed software also attached in Appendix 7.8 (Fig 7.8A).

Stator outer diameter	0.1651 m
Bore diameter	0.0990 m
Bore length	0.0564 m
Back of core	0.0099 m
Stator tooth width	0.0259 m
Rotor tooth width	0.0284 m
Rotor slot depth	0.0295 m
Stator slot depth	0.0231 m
Volume	0.0291 m^3
Air gap	0.000254 m
Turn per phase	1142
Power developed	100 watts
Efficiency	0.704
Torque average	13.56 Nm
Voltage	34.08 Volts

From the results, it can be seen that the power developed is 100 watts and torque average is 13.5 Nm. These values are acceptable based on the input speed specification (100 rpm). The efficiency from the results is 70.4% and voltage is 34.08 volts. Thus, in the design procedure it is preferable to choose the specifications with the highest efficiency but with low voltage. Bore diameter is evaluated if the starting values are known i.e speed, current loading, operating point (K_2) and K. The value of bore diameter from the CAD simulation is 0.099 m. This value isreasonablebased on starting values (speed = 100 watts, current loading = 25000, K_2 = 0.71 and K = 0.7). The air gap length is 0.254 mm and indicates that the small motor is developed in this CAD.

The motor parameters obtained from the CAD program simulation are used in static analysis to evaluate the magnetisation characteristics (flux linkage against current). The torque against current characteristics also evaluated to predict the performance of the motor.

Current (Amp)	Aligned flux linkage	Unaligned flux linkage	Torque (Nm)
1.0	1.993	0.183	2.710
2.0	2.185	0.366	6.184
3.0	2.294	0.549	9.505
4.0	2.372	0.732	12.572
5.0	2.432	0.915	15.253
6.0	2.482	1.097	17.745
7.0	2.526	1.277	19.872
8.0	2.559	1.453	21.457
9.0	2.593	1.629	23.001
10.0	2.626	1.805	24.565

Table 7.5: Shows the flux linkage and torque against current

The evaluation of aligned flux linkages can be very accurate, the same cannot be said for the unaligned values. The leakage fluxes and the path of the mutual flux complicate the accurate estimation of the unaligned flux linkages. The AFP technique has been used to accurately estimate the unaligned flux linkage. The graphs for both flux linkage and torque against current are shown in Appendix 7.8 (Fig 7.8B and Fig 7.8C).

The flux linkage and torque against current characteristics shown in Table 7.5 are used to evaluate the magnetisation curves at intermediate rotor positions (Stephenson and Corda Method [12] or Miller's Method [5]). This magnetisation curves can produce several graphs i.e flux linkage versus current at various angles, flux linkage versus rotor positions (with current as a parameter) and static torque versus rotor positions. These graphs are shown in Appendix 7.8(Fig 7.8E, Fig 7.8H and Fig 7.8I).

From Fig 7.8E, it can be seen that the individual flux linkage against cuurent curves are plotted at equally spaced intervals of rotor positions, the spacing between the curves are nearly uniform in region I ($45^0 \leq \theta \leq 54^0$), whereas in region II and region III, they are ($54^0 \leq \theta \leq 81^0$) and ($81^0 \leq \theta \leq 90^0$) respectively. One prominent characteristic of these curves is that the curves become bunched progressively close together towards the unaligned and aligned position respectively.

Fig 7.8H is derived by interpolating flux linkage/current/rotor positions to obtain flux linkage/rotor positions with current as a parameter. This model is more efficient to evaluate the motor performance of current limits which is the chopping current level or peak diode current. The instantaneous torque is plotted where current is constant in Fig 7.8I. It shows that the torque in region II is constant since the torque is proportional to the current.

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The data from the magnetisation curves are used in developing the loop conversion. The control parameters consist of voltage terminal, resistance, time interval, switch on angle, switch off angle and interval between angle.

The parameters are given as:

Voltage	34.08 Volts
Resistance	2.62 Ohm
Time interval	0.01 s
Theta on	45°
Theta off	70°
Theta interval	4.6°

The result of loop conversion as shown in the table below

Rotor position (°)	Current (Amp)	Flux linkage
45.0	0.025	0.005
49.5	1.387	0.345
54.0	2.410	0.649
58.5	3.073	0.927
63.0	3.178	1.186
67.5	2.849	1.444
72.0	2.552	1.710
76.5	0.361	1.302
81.0	0.226	0.951

The locus of flux linkage against current for energy conversion loops is shown in Appendix 7.8 (Fig 7.8F). From this locus, it can be seen that the operating speed is slow (100 rpm). Hence the phase current variation can be plotted as shown in Appendix 7.8(Fig 7.8G) where the peak current is obtained (3.2 A). Current waveform is nonsinusoidal and varies widely with operating conditions. The effective inductance of the circuit is small initially, allowing the current to build up rapidly to its maximum value (and to maximise its torque-producing effect)

Subsequently, the rising inductance and the motional emf cause the current to fall until the switch is opened at turn-off angle. Thereafter the current falls, the current than flows into the supply. Note that the direction of current never reverses. The angle between turn-on and turn-off angle is referred to as the conduction angle.

The torque waveform is dependent on the variation of phase current as shown in Appendix 7.8(Fig 7.8J). The electromagnetic or dynamic torque which forms the area of energy conversion loops is 4.95 Nm.

For the control of SRMs, it is helpful to begin by considering its 'natural' or 'inherent' characteristics (i.e that occurs under conditions of fixed supply voltage and fixed switching angles)[2]. The analogy with the dc series machine immediately points to the possiblity of control through terminal voltage or supply current. There are two further important parameters which are switch-on angle and switch-off angle. Control of these angles involves only the appropriate conditioning of timing pulse. In practice, control parameters are chosen so as to optimise overall system-performance (e.g to minimise current or to maximise efficiency).